Hamiltonian Formalism in Quantum Mechanics

Boris A. Kupershmidt

The University of Tennessee Space Institute, Tullahoma, TN 37388 USA
E-mail: bkupersh@utsi.edu

Received January 29, 1998

To Vladimir Igorevich Arnol’d with admiration, on occasion of his 60th birthday.

Abstract

Heisenberg motion equations in Quantum mechanics can be put into the Hamilton form. The difference between the commutator and its principal part, the Poisson bracket, can be accounted for exactly. Canonical transformations in Quantum mechanics are not, or at least not what they appear to be; their properties are formulated in a series of Conjectures.

1 Introduction

The motion equations of Classical mechanics, in the Hamilton form, are:

\[
\dot{q}_i = \frac{\partial H}{\partial p_i}, \quad \quad (1.1a)
\]

\[
\dot{p}_i = -\frac{\partial H}{\partial q_i}, \quad \quad (1.1b)
\]

Here \(i = 1, \ldots, N\), and \(H\), the Hamiltonian, is a function of the \(p_i\)'s and \(q_i\)'s, most often polynomial in the momenta \(p_i\)'s. The overdot, as usual, denotes the time derivative.

The motion equations of Quantum mechanics, in the Heisenberg form, are:

\[
\dot{q}_i = \hbar^{-1}\left[H, q_i\right], \quad \quad (1.2a)
\]

\[
\dot{p}_i = \hbar^{-1}\left[H, p_i\right]. \quad \quad (1.2b)
\]

Here \(H\) again is a “function” of the \(p_i\)'s and \(q_i\)'s; the latter, however, no longer commute between themselves but are, instead, subject to the commutation relations

\[
[p_k, q_\ell] = \hbar\delta_{k\ell}, \quad [p_k, p_\ell] = [q_k, q_\ell] = 0, \quad \quad (1.3)
\]
the complex number $\sqrt{-1}$ having been absorbed into $h$ for future convenience. The straight bracket notation stands for the commutator:

$$ [u, v] = uv - vu. \quad (1.4) $$

These two types of motion equations are known as not entirely unrelated. For example, if the $p_i$’s and the $q_i$’s are treated as operators, then the Classical equations (1.1) describe the motion of the mean values of these operators provided the Hamiltonian is quadratic in its arguments. (This is a Corollary of Ehrenfest’s Theorem. These and other mysteries are revealed in Messiah’s classic text on Quantum Mechanics [8].)

The first main result of this paper is an observation that the Quantum motion equations (1.2) can be recast into the Classical form (1.1) provided one properly defines the notion of partial derivatives entering into the RHS of the equations (1.1). This is done in the next Section. The main idea is to treat Quantum notions as special instances of noncommutative objects and then utilize noncommutative algebra concepts.

If the motion equations (1.1) and (1.2) are rewritten in the equivalent form as, respectively,

$$ \dot{F} = \{H, F\}, \quad (1.5) $$

$$ \dot{F} = h^{-1}[H, F], \quad (1.6) $$

where $F$ is an arbitrary function of the $p_i$’s and $q_i$’s and $\{\cdot, \cdot\}$ denotes the Poisson bracket:

$$ \{H, F\} = \sum_i \left( \frac{\partial H}{\partial p_i} \frac{\partial F}{\partial q_i} - \frac{\partial H}{\partial q_i} \frac{\partial F}{\partial p_i} \right), \quad (1.7) $$

one can ask whether these two forms are related in some precise manner. Certainly, one knows that the Poisson bracket is the “main part” of the commutator, in the sense that

$$ \lim_{h \to 0} h^{-1}[H, F] = \{H, F\}, \quad (1.8) $$

as a physicist would say, or

$$ \{H, F\} = h^{-1}[H, F] \pmod{h} \quad (1.9) $$

as is preferred by mathematicians. In Section 3 we shall verify that, when the number $N$ of degrees of freedom equals 1,

$$ h^{-1}[H, F] = \sum_{s \geq 1} \frac{(-h)^{s-1}}{s!} \left( \frac{\partial^s H}{\partial p^s} \frac{\partial^s F}{\partial q^s} - \frac{\partial^s F}{\partial p^s} \frac{\partial^s H}{\partial q^s} \right), \quad (1.10) $$

where the partial derivatives in the RHS are understood in the same sense, to be defined in Section 2, as those entering formulae (1.1) when considered noncommutatively. (The general case $N \geq 1$ is covered by formula (3.22).) We shall see that formula (1.10) is related to the definition of multiplication on the space of normally quantised Hamiltonians.

In Section 4 we consider the question of canonical transformations in Quantum mechanics, reformulate the Classical Jacobian conjecture into a symplectic object, quantize it, and state various generalizations of it.
2 Heisenberg as Hamilton in disguise

Let us first fix notations and conventions. Our basic number field $\mathcal{F}$ (such as $\mathbb{Q}$, $\mathbb{R}$, $\mathbb{C}$, etc.) will be of characteristic zero; this is not essential for results, but allows shortcuts in proofs. Instead of a field $\mathcal{F}$ one can take any associative ring (or $\mathbb{Q}$-algebra) commuting with the function-ring generators, but we shan’t travel this route either, to avoid interruptions by remarks. Our function rings will always be polynomial, again to bypass necessary pedantic comments; nothing much will change if we allow unspecified functions of the $q_i$’s (rational, algebraic, etc.) as is the case in practical mechanics, because all our formulae will describe identities between differential operators, and the said identities remain true no matter what objects these differential operators are allowed to act upon.

We start with the associative ring

$$C = C_u = \mathcal{F}\langle u_1, \ldots, u_m \rangle,$$

consisting of polynomials in noncommuting variables $u_1, \ldots, u_m$; all with coefficients in $\mathcal{F}$. (The coefficients are always assumed to commute with the field variables $u_i$’s.) If $x \in C$ then $\hat{L}_x$ and $\hat{R}_x$ denote the operators of left and right multiplication by $x$ in $C$:

$$\hat{L}_x(y) = xy, \quad \hat{R}_x(y) = yx, \quad \forall \ x, y \in C. \quad (2.2)$$

The associative ring generated by the operators $\hat{L}_x$ and $\hat{R}_x$, for all $x$ in $C$, is denoted $Op_0(C)$. \quad (2.3)

We shall utilize the following useful elements in this operator ring ([7]): For any $H \in C$,

$$\frac{\partial \sim H}{\partial u_k} \in Op_0(C) \quad (2.4)$$

is the following operator:

$$\frac{\partial \sim H}{\partial u_k}(x) = \frac{d}{d\epsilon} \bigg|_{\epsilon=0} \left( H_{|_{u_k \to u_k+\epsilon x}} \right), \quad x \in C. \quad (2.5)$$

Alternatively, we can describe the operation $\frac{\partial \sim}{\partial u_k}$ itself as a derivation (over $\mathcal{F}$) of $C$ into $Op_0(C)$:

$$\frac{\partial \sim}{\partial u_k} : C \to Op_0(C), \quad (2.6a)$$

which acts on the generators of $C$ by the rule

$$\frac{\partial \sim}{\partial u_k}(u_s) = \delta_{ks}. \quad (2.6b)$$

If $X \in \text{Der}(C)$ is a derivation of $C$ (over $\mathcal{F}$) then, obviously,

$$X(H) = \sum_k \frac{\partial \sim H}{\partial u_k}(X(u_k)) =: \frac{\partial \sim H}{\partial u}(X), \quad \forall \ H \in C. \quad (2.7)$$
The same equality can be described in a more familiar form. First, let us write suggestively, but imprecisely,

\[ X = \sum_k X(u_k) \frac{\partial}{\partial u_k}, \quad \forall X \in \text{Der}(C), \]  

(2.8)

to mean nothing more than \( X \in \text{Der}(C) \) is uniquely determined by the action of \( X \) on the \( u_k \)'s. Second, let

\[ \Omega^1(C) = \left\{ \sum_{ks} \varphi_{ks} du_k \psi_{ks} \mid \varphi_{ks}, \psi_{ks} \in C \right\} \]  

(2.9)

be the \( C \)-bimodule of 1-forms over \( C \), with the universal derivation \( d : C \to \Omega^1(C) \) acting naturally on the generators of \( C \) by the rule

\[ d(u_k) = du_k, \quad k = 1, \ldots, m. \]  

(2.10)

Then

\[ d(H) = \sum_k \frac{\partial^\sim H}{\partial u_k}(du_k), \]  

(2.11)

where \( \frac{\partial^\sim H}{\partial u_k} \), as an element of \( Op_0(C) \), is extended naturally to act on any \( C \)-bimodule, in this case \( \Omega^1(C) \). If we now define the familiar pairing

\[ \Omega^1(C) \times \text{Der}(C) \to C \]  

(2.12)

by the rule

\[ \left\langle \sum \varphi_{ks} du_k \psi_{ks}, X \right\rangle = \left( \sum \varphi_{ks} du_k \psi_{ks} \right)(X) = \sum \varphi_{ks} X(u_k) \psi_{ks}, \]  

(2.13)

then formula (2.7) can be rewritten in the familiar form

\[ X(H) = \left\langle dH, X \right\rangle = dH(X). \]  

(2.14)

So far we haven’t met any \( p \)'s or \( q \)'s. We shall get to them at the very end of this Section, for more general formulae we work with now are more transparent and easier to handle.

For lack of better notation, we shall denote by \( \frac{\partial H}{\partial u_k} \) the following element of the ring \( C \), not of the ring \( Op_0(C) \):

\[ \frac{\partial H}{\partial u_k} = \frac{\partial^\sim H}{\partial u_k}(1) = \frac{d}{d\epsilon} \bigg|_{\epsilon=0} \left( H \bigg|_{u_k \to u_k + \epsilon} \right). \]  

(2.15)

If \( H \) is a homogeneous polynomial of degree \( \ell = \text{deg}(H) \) and \( X^{rad} \in \text{Der}(C) \) is the radial derivation of \( C \):

\[ X^{rad}(u_k) = u_k, \quad k = 1, \ldots, m, \]  

(2.16)
then we have the following noncommutative analog of the Euler Theorem on homogeneous functions:

\[ X^{\text{rad}}(H) = \left( \sum u_k \frac{\partial}{\partial u_k} \right) (H) = \ell H = \deg(H)H. \]  

(2.17)

Suppose now that we impose some commutation relations on the \( u_i \)'s. This means that we are given a finite or infinite system of polynomials (or, in more general circumstances, power series, etc.)

\[ R_r = \sum_{\sigma} c_{r\sigma} u^{\sigma}, \quad c_{r\sigma} \in \mathcal{F}, \]  

(2.18a)

\[ u^{\sigma} := u_{\sigma_1} \ldots u_{\sigma_s} \text{ for } \sigma = (\sigma_1, \ldots, \sigma_s), \quad \sigma_c = 1, \ldots, m, \]  

(2.18b)

and we form the factor-ring

\[ C_u^{\text{new}} = C_u / \mathcal{I}_R, \]  

(2.19)

where \( \mathcal{I}_R \) is the two-sided ideal in \( C_u \) generated by the polynomials \( R_r \)'s. If we want now to consider some “motion equations” in the ring \( C_u^{\text{new}} \), i.e., elements of the Lie algebra \( \text{Der}(C_u^{\text{new}}) \), we have to look at only those derivations \( X \in \text{Der}(C_u) \) which preserve the ideal \( \mathcal{I}_R \). There exists quite a number of such special derivations, namely the elements

\[ \{ \text{ad}_F := \hat{L}_F - \hat{R}_F | F \in C_u \}. \]  

(2.20)

Indeed, any element of the ideal \( \mathcal{I}_R \) is a finite sum of the terms

\[ \{ \varphi P_r \psi | \varphi, \psi \in C \}. \]  

(2.21)

But then

\[ \text{ad}_F(\varphi P_r \psi) = F \varphi P_r \psi - \varphi P_r \psi F \]  

(2.22)

is again an element of \( \mathcal{I}_R \). In the physical language, if

\[ \dot{u}_i = [F, u_i], \quad i = 1, \ldots, m, \]  

(2.23)

so that

\[ u_i(t + \Delta t) = u_i(t) + \Delta t[F, u_i(t)] + O(\Delta t)^2, \]  

(2.24)

then

\[ \sum c_{r\sigma} u^{\sigma}(t + \Delta t) = \sum c_{r\sigma} u^{\sigma}(t) + \Delta t \left[ F \sum c_{r\sigma} u^{\sigma}(t) \right] + O(\Delta t)^2, \]  

(2.25)

so that the commutation relations on the \( u_i \)'s are preserved in time.

There may exist also some other derivations of the ring \( C_u \) which preserve a particular ideal \( \mathcal{I}_R \). This is the case we are interested in, with the derivations in question being the “partial derivatives” \( \frac{\partial}{\partial u_k} \) (2.15).
Lemma 2.26. Suppose we are given the relations

\[ P_{ij} = u_i u_j - u_j u_i - c_{ij}, \quad c_{ij} = -c_{ij} \in \mathcal{F}. \]  

(2.27)

Then the derivations \( \frac{\partial}{\partial u_k} \) preserve the two-sided ideal generated by these relations.

Proof. We have

\[ \frac{\partial}{\partial u_k} (P_{ij}) = \delta_{ik} u_j + \delta_{jk} u_i - \delta_{jk} u_i - \delta_{ik} u_j = 0, \]  

(2.28)

and hence

\[ \frac{\partial}{\partial u_k} (\varphi P_{ij} \psi) = \frac{\partial \varphi}{\partial u_k} P_{ij} \psi + \varphi P_{ij} \frac{\partial \psi}{\partial u_k} \in \mathcal{I} \mathcal{R}. \]  

(2.29)

Corollary 2.30. In the ring \( C^{\text{new}}_u \):

\[ C^{\text{new}}_u = \mathcal{F}(u_1, \ldots, u_m) / ([u_i, u_j] = c_{ij}) \]  

(2.31)

the objects

\[ \left\{ \frac{\partial H}{\partial u_k} \bigg| H \in C^{\text{new}}_u, \quad k = 1, \ldots, m \right\} \]  

(2.32)

are well-defined and satisfy formulae

\[ \text{ad}_{u_i}(H) = \sum_k \frac{\partial H}{\partial u_k} c_{ik}. \]  

(2.33)

Proof. By formula (2.7),

\[ \text{ad}_{u_i}(H) = \sum_k \frac{\partial}{\partial u_k} \left( \text{ad}_{u_i}(u_k) \right) \text{ in } C_u. \]  

(2.34)

By formula (2.27),

\[ [u_i, u_j] = c_{ij} \text{ in } C^{\text{new}}_u. \]  

(2.35)

Hence, now in \( C^{\text{new}}_u \),

\[ \text{ad}_{u_i}(H) = \sum_k \frac{\partial}{\partial u_k} (c_{ik}) = \sum_k c_{ik} \frac{\partial}{\partial u_k} (1) = \sum_k c_{ik} \frac{\partial H}{\partial u_k}. \]  

(2.36)

Corollary 2.37. Consider the case where \( \mathcal{F} \) is replaced by

\[ \mathcal{F}_h = \mathcal{F}[\hbar], \]  

(2.38)

the ring of formal power series in \( h \), and the \( u_i \)'s are taken to be the \( p_i \)'s and the \( q_i \)'s, with the commutation relations

\[ [p_i, q_j] = h\delta_{ij}, \quad [p_i, p_j] = [q_i, q_j] = 0. \]  

(2.39)

Then the Heisenberg motion equations (1.2) take the Hamiltonian form (1.1).
Proof. We can transform formulae (1.2) as follows:

\[
\dot{q}_i = h^{-1}[H, q_i] = -h^{-1}\text{ad}_{q_i}(H) \quad \text{[by (2.33,39)]} = -h^{-1} \frac{\partial H}{\partial p_i}(-h) = \frac{\partial H}{\partial p_i},
\]

\[
\dot{p}_i = h^{-1}[H, p_i] = -h^{-1}\text{ad}_{p_i}(H) = -h^{-1} \frac{\partial H}{\partial q_i} h = -\frac{\partial H}{\partial q_i}.
\]

Remark 2.40. Like in the commutative algebra and analysis, partial derivatives commute between themselves both in \(C_u\) and \(C_{\text{new}}^u\):

\[
\frac{\partial^2 H}{\partial u_i \partial u_j} = \frac{\partial^2 H}{\partial u_j \partial u_i}. \quad \text{(2.41)}
\]

This is clear from the definition (2.15).

Remark 2.42. The operator-valued partial derivatives \(\partial^\sim\frac{\partial}{\partial u_k}\) satisfy the chain rule: If the \(u_k\)'s are functions of the \(\varphi_\alpha\)'s then

\[
\frac{\partial^\sim H}{\partial \varphi_\alpha} = \sum_k \frac{\partial^\sim H}{\partial u_k} \frac{\partial^\sim u_k}{\partial \varphi_\alpha}. \quad \text{(2.43)}
\]

Indeed,

\[
u_k(\varphi_1, \ldots, \varphi_\alpha + \epsilon x, \ldots) = u_k(\varphi) + \epsilon \frac{\partial^\sim u_k}{\partial \varphi_\alpha}(x) + O(\epsilon^2).
\]

Therefore,

\[
H(u_1(\varphi_\alpha + \epsilon x), \ldots, u_m(\varphi_\alpha + \epsilon x)) = H(u(\varphi) + \epsilon \frac{\partial^\sim u_1}{\partial \varphi_\alpha}(x) + O(\epsilon^2), \ldots)
\]

\[
= H(u(\varphi)) + \epsilon \sum_k \frac{\partial^\sim H}{\partial u_k} \left( \frac{\partial^\sim u_k}{\partial \varphi_\alpha}(x) \right),
\]

so that

\[
\frac{d}{d\epsilon} \bigg|_{\epsilon=0} H(\varphi_1, \ldots, \varphi_\alpha + \epsilon x, \ldots) = \frac{\partial^\sim H}{\partial \varphi_\alpha}(x) = \sum_k \frac{\partial^\sim H}{\partial u_k} \frac{\partial^\sim u_k}{\partial \varphi_\alpha}(x), \quad \forall x, \quad \text{(2.46)}
\]

and formula (2.43) follows.

3 Commutator vs Poisson bracket

On the way to verify formula (1.10), we shall prove first a more general statement. Suppose we impose the relations

\[
[u_i, u_j] = \hbar c_{ij}, \quad 1 \leq i, j \leq m, \quad c_{ij} = -c_{ij} \in \mathcal{F},
\]

on the ring \(\mathcal{F}_h(u_1, \ldots, u_m)\). We can think of these relations as the rules allowing us to reduce every polynomial in the \(u_i\)'s to a specific lexicographic form by choosing an ordering among the generators \(u_i\)'s. The original relations (3.1), in the form

\[
u_i u_j = u_j u_i + \hbar c_{ij},
\]

(3.2)
imply, and are equivalent to, the series of relations
\[ u_n^i u_j^m = \sum_{s \geq 0} (hc_{ij})^s \left( \frac{u_i^{m-s}}{(m-s)!} \frac{u_j^{n-s}}{(n-s)!} \right), \quad n, m \in \mathbb{N}. \]  \hspace{1cm} (3.3)

This series of relations, in turn, is equivalent to the single formal relation
\[ E\lambda^i u E\mu^j u = E\mu^i u E\lambda^j u e^{h(\lambda, \mu)} \]  \hspace{1cm} (3.4)
in \( \mathcal{F}_h \langle u_1, \ldots, u_m \rangle[[\lambda, \mu]] \), where
\[ E\lambda^i u = e^{\lambda_1 u_1} \ldots e^{\lambda_m u_m}, \]  \hspace{1cm} (3.5)
\[ (\lambda, \mu) = \sum c_{ij} \lambda_i \mu_j = -\langle \mu, \lambda \rangle. \]  \hspace{1cm} (3.6)

Lemma 3.7. Define the coefficients \( \{\theta_{\sigma \sigma'}\} \) in \( \mathcal{F} \) by the identity:
\[ \sum_{s \geq 1} \frac{(-h)^{s-1}}{s!} (\lambda, \mu)^s = \sum_{\sigma \sigma'} \theta_{\sigma \sigma'} \lambda^\sigma \mu^\sigma \frac{(-h)^{-1+|\sigma|+|\sigma'|/2}}{(|\sigma| + |\sigma'|)/2)!}, \]  \hspace{1cm} (3.8)
where
\[ \lambda^\sigma = \lambda_1^{\sigma_1} \ldots \lambda_m^{\sigma_m} \quad \text{for} \quad \sigma = (\sigma_1, \ldots, \sigma_m), \quad \sigma_i \in \mathbb{Z}_+, \]  \hspace{1cm} (3.9a)
\[ |\sigma| = \sigma_1 + \cdots + \sigma_m. \]  \hspace{1cm} (3.9b)

Then
\[ h^{-1}[H, F] = \sum_{s \geq 1} \frac{(-h)^{s-1}}{s!} \sum_{|\sigma| = |\sigma'| = s} \theta_{\sigma \sigma'} \frac{\partial^{\sigma} H}{\partial u^\sigma} \frac{\partial^{\sigma'} F}{\partial u^{\sigma'}}, \]  \hspace{1cm} (3.10)
where
\[ \frac{\partial^{\sigma} H}{\partial u^\sigma} = \frac{\partial^{\sigma_1}}{\partial u_1^{\sigma_1}} \cdots \frac{\partial^{\sigma_m}}{\partial u_m^{\sigma_m}}(H) \quad \text{for} \quad \sigma = (\sigma_1, \ldots, \sigma_m). \]  \hspace{1cm} (3.11)

Proof. It’s enough to check formula (3.10) for the case
\[ H = E\lambda^i u, \quad F = E\mu^j u. \]  \hspace{1cm} (3.12)

Then
\[ h^{-1}[H, F] = h^{-1} \left( E\lambda^i u E\mu^j u - E\mu^i u E\lambda^j u \right) \]
\[ \overset{[\text{by (3.4)}]}{=} hF \frac{1 - e^{h(\mu, \lambda)}}{h} = hF \frac{1 - e^{-h(\lambda, \mu)}}{h} = \frac{e^{-h(\lambda, \mu)} - 1}{-h} HF \]
\[ = \sum_{s \geq 1} \frac{(-h)^{s-1}}{s!} (\lambda, \mu)^s HF \overset{[\text{by (3.8)}]}{=} \sum_{\sigma \sigma'} \theta_{\sigma \sigma'} \lambda^\sigma \mu^\sigma \frac{(-h)^{-1+\cdots}}{(|\sigma| + |\sigma'|)/2)!} \frac{\partial^{\sigma} H}{\partial u^\sigma} \frac{\partial^{\sigma'} F}{\partial u^{\sigma'}}. \]
The terms with $s = 1$ in the RHS of formula (3.10) comprise the Poisson bracket part, for formula (3.8) implies that

$$\theta_{ij} = c_{ij}. \tag{3.13}$$

If we now specialize to the Quantum case when $[p_i, q_j] = h\delta_{ij}$, we will not get formula (1.10), for in the RHS of formula (3.10) $H$ stands always to the left of $F$ and the $(H, F)$ skewsymmetry is thus hidden. But we can emulate the proof of Lemma 3.7. First, we convert the relations

$$[p_i, q_j] = h\delta_{ij}, \quad [p_i, p_j] = [q_i, q_j] = 0, \tag{3.14}$$

into the single formal relation

$$e^{\lambda \cdot p} e^{\alpha \cdot q} = e^{h\lambda \cdot \alpha} e^{\alpha \cdot q} e^{\lambda \cdot p}. \tag{3.15}$$

Next, we take

$$H = e^{\alpha \cdot q} e^{\lambda \cdot p}, \quad F = e^{\beta \cdot q} e^{\mu \cdot p}. \tag{3.16}$$

Now, consider the operators

$$\mathcal{O}_{HF} = \frac{\partial H}{\partial p} \cdot \frac{\partial F}{\partial q} : HF \mapsto \sum_i \frac{\partial H}{\partial p_i} \frac{\partial F}{\partial q_i}, \tag{3.17a}$$

$$\mathcal{O}_{FH} = \frac{\partial F}{\partial p} \cdot \frac{\partial H}{\partial q} : FH \mapsto \sum_i \frac{\partial F}{\partial p_i} \frac{\partial H}{\partial q_i}. \tag{3.17b}$$

Let us verify that

$$e^{-h\mathcal{O}_{HF}} (HF) = (\text{smbl}(H)\text{smbl}(F))_{\text{normal}}, \tag{3.18}$$

where, for $H \in \mathcal{C}_{\text{new}}^u$, $\text{smbl}(H) \in \mathcal{F}[u_1, \ldots, u_m]$ is the symbol of $H$ which results by letting $h$ vanish (in $\mathcal{C}_{\text{new}}^u/(h\mathcal{C}_{\text{new}}^u)$), and the subscript “normal” denotes the normal quantization, with the $q_i$’s standing to the left of the $p_i$’s. Indeed, for $H$ and $F$ given by formula (3.16),

$$e^{-h\mathcal{O}_{HF}} (HF) = \sum_{s \geq 0} \frac{(-h\lambda \cdot \beta)^s}{s!} HF = e^{(\alpha + \beta) \cdot q} e^{(\lambda + \mu) \cdot p}. \tag{3.19}$$

Since

$$\text{smbl}(H)\text{smbl}(F) = \text{smbl}(F)\text{smbl}(H), \tag{3.20}$$

formula (3.18) implies:

$$e^{-h\mathcal{O}_{HF}} (HF) = e^{-h\mathcal{O}_{FH}} (FH), \tag{3.21}$$

so that

$$h^{-1}[H, F] = h^{-1}(HF - FH) = \frac{e^{-h\mathcal{O}_{HF}} - 1}{-h} (HF) - \frac{e^{-h\mathcal{O}_{FH}} - 1}{-h} (FH)$$

$$= \sum_{s \geq 1} \frac{(-h)^{s-1}}{s!} ((\mathcal{O}_{HF})^s(HF) - (\mathcal{O}_{FH})^s(FH)). \tag{3.22}$$
For the case when the number of degrees of freedom \( N = 1 \),

\[
O_{HF}(HF) = \frac{\partial H}{\partial p} \frac{\partial F}{\partial q},
\]

(3.23)

and formula (3.22) yields formula (1.10).

**Remark 3.24.** Formula (3.21) implies that we have a symmetric bilinear form in the *noncommutative* ring \( C^{\text{new}}_{p,q} \):

\[
(H, F) = e^{-\hbar O_{HF}(HF)}.
\]

(3.25)

There exists another attractive bilinear form on this ring, this time with values in the *commutative* ring \( \mathcal{F}[q_i][[\hbar]] \):

\[
(H, F) = \text{Res}(HF^\dagger),
\]

(3.26)

where

\[
\text{Res} \left( \sum c_{\sigma'} q^\sigma p^{\sigma'} \right) := \sum c_{00} q^\sigma,
\]

(3.27)

and \( \dagger \) is an antiinvolution (over \( \mathcal{F}_h \)):

\[
(HF)^\dagger = F^\dagger H^\dagger,
\]

(3.28)

defined on the generators \( q_i \)'s and \( p_i \)'s by the rule

\[
q_i^\dagger = q_i, \quad p_i^\dagger = -p_i, \quad i = 1, \ldots, N.
\]

(3.29)

The bilinear form \((H, F)\) (3.26) is not symmetric in the *linear algebra* sense, but it is symmetric in the *differential algebra* sense:

\[
(H, F) \sim (F, H),
\]

(3.30)

where, for elements \( a, b \in \mathcal{F}[q_i][[\hbar]] \), we write

\[
a \sim b \quad \text{to mean} \quad (a - b) \in \sum_i \text{Im} \frac{\partial}{\partial q_i}.
\]

(3.31)

To prove formula (3.30), we take \( H \) and \( F \) given by formula (3.16). Then

\[
(H, F) = \text{Res}(HF^\dagger) = \text{Res} \left( e^{\alpha q e^\lambda p e^{-\mu p e^{\beta q}}} \right) = \text{Res} \left( e^{(\alpha + \beta) q e^{(\lambda - \mu) p e^{(\lambda - \mu) \beta \hbar}}} \right) = e^{(\lambda - \mu) \beta \hbar} e^{(\alpha + \beta) q}.
\]

(3.32)

Hence,

\[
(F, H) = e^{(\mu - \lambda) \alpha \hbar} e^{(\alpha + \beta) q} = e^{(\mu - \lambda) (\alpha + \beta) \hbar} (H, F)
\]

\[
= e^{\hbar (\mu - \lambda) \partial/\partial q} (H, F) \sim (H, F).
\]

(3.33)
4 Canonical transformations, special and general

If $M$ is a smooth manifold and $T^*M$ is the cotangent bundle (= the phase space) of $M$, then any transformation

$$\varphi : M \rightarrow M$$

is uniquely lifted to a transformation

$$\tilde{\varphi} : T^*M \rightarrow T^*M$$

covering $\varphi$, by the requirement that the canonical 1-form

$$\rho = pdq$$

on $T^*M$ be preserved:

$$\tilde{\varphi}^* (\rho) = \rho.$$ (4.4)

Re-expressing this picture analytically/algebraically, we start with an automorphism $\Phi$ of the ring $C_q$

$$\Phi : C_q \rightarrow C_q, \quad C_q = \mathcal{F}[q_1, \ldots, q_N], \ C^\infty(q_1, \ldots, q_N), \ldots$$

$$\Phi(q_i) = Q_i = Q_i(q_1, \ldots, q_N), \quad i = 1, \ldots, N,$$ (4.6)

and then determine the elements

$$\tilde{\Phi}(p_i) = P_i = P_i(q, p)$$ (4.7)

from the requirement that

$$pdq = PdQ :$$

$$\sum_j p_j dq_j = \sum_i P_i dQ_i = \sum_i P_i Q_{i,j} dq_j.$$ (4.9)

Thus,

$$p_j = \sum_i P_i Q_{i,j}, \quad j = 1, \ldots, N.$$ (4.10)

Denote by

$$J = J_{Q_i q_j} = \left( \frac{\partial Q_i}{\partial q_j} \right)$$

the Jacobian of the map $\Phi$. The transformation formulae (4.10) can be rewritten in one of the equivalent forms:

$$p^i = P^i J,$$ (4.12a)

$$P^i = p^i J^{-1},$$ (4.12b)
Hamiltonian Formalism in Quantum Mechanics

\[ P = (J^{-1})^t p, \]

where \( p, P, q, Q \) are thought of as column-vectors. Since the canonical 1-form \( pdq \) is preserved, the symplectic 2-form \( dp \wedge dq \) is preserved as well. Therefore, the basic Poisson brackets are also preserved:

\[ \{P_i, P_j\} = \{Q_i, Q_j\} = 0, \quad \{P_i, Q_j\} = \delta_{ij}. \]  

(4.13)

**Remark 4.14.** If one concentrates on the preservation of the Poisson brackets only, that is, of the 2-form \( dq \wedge dq \) rather than the canonical 1-form \( pdq \), the uniqueness of the lifting of \( \varphi \) into \( \overline{\varphi} \) no longer holds. For example, we can replace formula (4.4) by the relation

\[ \overline{\varphi}^*(\rho) = \rho + \omega, \]  

(4.15)

where \( \omega \) is a closed 1-form on \( M \) lifted into \( T^*M \). Taking

\[ \omega = d(f), \quad f \in \mathcal{C}_q, \]  

(4.16)

we find, instead of formula (4.10), the relations

\[ p_j = \sum P_i Q_{i,j} + f_j, \]  

(4.17)

\[ P = (J^{-1})^t (p - \nabla(f)). \]  

(4.18)

We shall see below that such nonuniqueness is *unavoidable* in Quantum mechanics.

**Lemma 4.19.** Formulae (4.6,12c) preserve the Quantum commutation relations

\[ [q_i, q_j] = [p_i, p_j] = 0, \quad [p_i, q_j] = \hbar \delta_{ij}, \quad 1 \leq i, j \leq N. \]  

(4.20)

**Proof.** Obviously,

\[ [Q_i, Q_j] = 0. \]  

(4.21)

Next,

\[ [P_i, Q_j] = \left[ \sum_\alpha (J^{-1})^t_\alpha p_\alpha, Q_j \right] = \sum_\alpha (J^{-1})_\alpha J_{j,\alpha} = h \sum_\alpha (J^{-1})_\alpha J_{j,\alpha} = h \delta_{ij}, \]  

(4.22)

Finally,

\[ P_i P_j = \sum_\alpha (J^{-1})_\alpha p_\alpha J^{-1}_\beta_\alpha P_\beta = \sum_\alpha (J^{-1})_\alpha \left\{ (J^{-1})_\beta J_{j,\alpha} + h (J^{-1})_\beta J_{j,\alpha} \right\} p_\beta, \]  

(4.23)

whence

\[ h^{-1}[P_i, P_j] = \sum_\beta \left( \sum_\alpha (J^{-1})_\alpha J^{-1}_\beta J_{j,\alpha} - \sum_\nu (J^{-1})_{\nu j} (J^{-1})_\beta J_{\nu,\alpha} \right) p_\beta. \]  

(4.24)

Now,

\[ (J^{-1})_{\beta j,\alpha} = -(J^{-1} J_{\alpha j} J^{-1})_{\beta j} = -\sum_\mu (J^{-1})_{\beta \mu} J_{\mu \alpha} (J^{-1})_{\nu j}, \]  

(4.25a)
and thus
\begin{equation}
(J^{-1})_{\beta i, \nu} = - \sum_{\mu \alpha} (J^{-1})_{\beta \mu} J_{\mu \alpha, \nu} (J^{-1})_{\alpha i}.
\end{equation}
(4.25b)

Substituting formulae (4.25) into formula (4.24) and noticing that
\begin{equation}
J_{\mu \nu, \alpha} = \frac{\partial^2 Q_\mu}{\partial q_\nu \partial q_\alpha} = J_{\mu \alpha, \nu},
\end{equation}
(4.26)
we find that
\begin{equation}
[P_i, P_j] = 0.
\end{equation}
(4.27)

The nonuniqueness of quantum formulae (4.12c) can be demonstrated in two ways.

\textbf{Lemma 4.28.} \textit{The transformation}
\begin{equation}
Q_i = q_i, \quad P_i = p_i + g, \quad i = 1, \ldots, m, \quad g \in C_q,
\end{equation}
(4.29)
\textit{preserves the quantum commutation relations (4.20).}

\textbf{Proof.} We have
\begin{equation}
[P_i, P_j] = [p_i + g, p_j + g] = hg_{ij} - hg_{ji} = 0,
\end{equation}
(4.30)
and the rest of the relations are obviously satisfied.

\textbf{Lemma 4.31.} \textit{The transformation}
\begin{align}
Q_i &= Q_i(q), \quad \tag{4.32a} \\
P_i &= \sum_\alpha p_\alpha (J^{-1})_{\alpha i}, \quad i = 1, \ldots, N, \tag{4.32b}
\end{align}
is also a quantum canonical transformation.

\textbf{Proof.} (A) The new formulae (4.32) are just the mirror image of the old ones, (4.6,12c), and \dag is an (anti)isomorphism. (B) Alternatively, we can straightforwardly calculate like in the proof of Lemma 4.19, and keep all the \(p_\alpha\)'s to the left of the \(q_\beta\)'s.

Thus, given a transformation \(\Phi : C_q \to C_q\), we have two different lifts of it into quantum canonical maps, \(\Phi_r\) (4.6,12c), and \(\Phi_\ell\) (4.32):
\begin{align}
\Phi_r(q_i) &= Q_i(q), \quad \Phi_r(p_i) = \sum_\alpha (J^{-1})_{\alpha i} p_\alpha, \quad \tag{4.33} \\
\Phi_\ell(q_i) &= Q_i(q), \quad \Phi_\ell(p_i) = \sum_\alpha p_\alpha (J^{-1})_{\alpha i}. \quad \tag{4.34}
\end{align}

How are these two maps related? Let us consider the composition \(\Psi = \Phi_r \Phi_\ell^{-1}\):
\begin{equation}
\Psi(q_i) = q_i, \quad \Psi(p_i) = \sum_{\alpha \beta} (J^{-1})_{\alpha \beta} p_\alpha J_{\beta i}, \quad 1 \leq i \leq N.
\end{equation}
(4.35)
Lemma 4.36.

\[ \Psi(p) = p + h \nabla(g), \quad (4.37a) \]
\[ g = \ln \det(J). \quad (4.37b) \]

Proof. From formulae (4.35) we find:

\[ \Psi(p_i) = \sum (J^{-1})_{\alpha\beta} \{J_{\beta i} p_\alpha + h J_{\beta i, \alpha}\} = p_i + h \sum (J^{-1})_{\alpha\beta} J_{\beta i, \alpha}. \quad (4.38) \]

But

\[ \sum (J^{-1})_{\alpha\beta} J_{\beta i, \alpha} = \sum (J^{-1})_{\alpha\beta} J_{\beta \alpha, i} = \text{Tr} \left( J^{-1} J_i \right) \quad (4.39) \]

[by formula (4.42) below]

Remark 4.40. Recall that if \( A \in \text{Mat}_n(C_q) \) then

\[ d(\ln \det(A)) = \text{Tr}(A^{-1} dA), \quad (4.41) \]

in the sense that

\[ (\ln \det(A))_{i \ell} = \text{Tr}(A^{-1} A_{i \ell}) = \sum (A^{-1})_{\alpha \beta} A_{\beta \alpha, i}. \quad (4.42) \]

Indeed, Let \( B = \ln(A) \), so that \( A = e^B \). Then

\[ \text{Tr}(A^{-1} dA) = \text{Tr} \left( e^{-B} d(e^B) \right) = \text{Tr} \left( e^{-B} \sum \frac{B^s d(B) B^r}{(r + s + 1)!} \right) \]
\[ = \text{Tr} \left( e^{-B} \sum \frac{B^r B^s d(B)}{(r + s + 1)!} \right) = \text{Tr} \left( e^{-B} \sum \frac{B^r d(B)}{r!} \right) = \text{Tr}(dB) \]
\[ = d \text{Tr}(B) = d(\ln \det(e^B)) = d(\ln \det(A)) \]

Remark 4.43. Formula (4.41) is rational in \( A \). An equivalent formulation, regular in \( A \), is

\[ d(\det(A)) = \text{Tr}(\text{adj}(A) dA), \quad (4.44) \]

where \( \text{adj}(A) \) is the adjugate matrix of \( A \):

\[ \text{adj}(A) A = A \text{adj}(A) = \det(A) \mathbf{1}. \quad (4.45) \]

Remark 4.46. Which one of the maps \( \Phi_r \) or \( \Phi_\ell \) is right in practice? Unfortunately, this is the sort of question akin to the problem of “right” quantization, that is to say, a wrong and misleading one. The “right” answer depends on the problem at hand, i.e., the Hamiltonian, and it may be nonunique nonetheless. I shall leave an elaboration of this point to the future. Let us consider instead an instructive case of the mechanical Hamiltonians, those of the form

\[ H = \sum a^{ij}(Q) P_i P_j + V(Q). \quad (4.47) \]
It is well-known in Quantum mechanics that if $P_k$’s are treated as $\frac{\partial}{\partial Q_k}$’s (recall that $\sqrt{-1}$ has been absorbed into $h$) then the selfadjoint form of $H$ is

$$H = \sum P_i a_{ij}^{(Q)} P_j + V(Q).$$

(4.48)

In other words,

$$H^\dagger = H.$$  

(4.49)

How does one transform such an $H$ under a change of variables $q_i \mapsto \Phi(q_i) = Q_i(q)$ (4.6), and still preserve the selfadjointness of $H$? Let us look at the simple example of a free particle in polar coordinates:

$$x = r \cos \theta, \quad y = r \sin \theta,$$

(4.50a)

$$J = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & r \end{pmatrix} \Rightarrow J^{-1} = \begin{pmatrix} 1 & 0 \\ 0 & r^{-1} \end{pmatrix} \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}. $$

(4.50b)

Thus, for the left form (4.34) we get

$$(p_x, p_y) = (p_r, p_\theta) \begin{pmatrix} 1 & 0 \\ 0 & r^{-1} \end{pmatrix} \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

$$= (p_r \cos \theta - p_\theta r^{-1} \sin \theta, \ p_r \sin \theta + p_\theta r^{-1} \cos \theta).$$

(4.51)

Hence, for the right form (4.33) we obtain

$$(p_x, p_y) = (\cos \theta p_r - r^{-1} \sin \theta p_\theta, \sin \theta p_r + r^{-1} \cos \theta p_\theta).$$

(4.52)

Now, the Hamiltonian $p_x^2 + p_y^2$ becomes:

$$p_x^2 + p_y^2 = p_r^2 + r^2 p_\theta^2 - hp_r r^{-1} \quad \text{(left form),}$$

(4.53l)

$$p_x^2 + p_y^2 = p_r^2 + r^2 p_\theta^2 + hp_r \quad \text{(right form),}$$

(4.53r)

and neither of these is physically palatable by virtue of not being selfadjoint. This observation seems to suggest that a substantial fraction of literature on Quantum mechanics is beside the point. What the point or points is or are I’ll again leave for the future can-of-worms operations. Let us return to the mechanical Hamiltonian $H$ (4.48): how should it transform in order to preserve its selfadjointness? We have seen above that neither the left nor the right transformation is satisfactory.

**Lemma 4.54.** Denote the left and right transformations as

$$P_i^l = \sum p_\alpha (J^{-1})_{ai}^\alpha, \quad P_i^r = \sum (J^{-1})_{ai}^\alpha p_\alpha.$$ 

(4.55)

Set

$$H^{lr} = \sum P_i^l a_{ij}^{(Q)} P_j^r, \quad H^{rl} = \sum P_i^r a_{ij}^{(Q)} P_j^l.$$ 

(4.56)

Then

$$(H^{lr})^\dagger = H^{lr}, \quad (H^{rl})^\dagger = H^{rl}.$$ 

(4.57)
Proof.

\[(P_\ell^i)^\dagger = -P_r^i, \quad (P_r^i)^\dagger = -P_\ell^i.\]  

(4.58)

In coordinates,

\[H^{\ell\ell} = \sum p_\alpha (J^{-1})_{\alpha i} a^{ij}(Q) (J^{-1})_{\beta j} p_\beta,\]  

(4.59)

\[H^{r\ell} = \sum (J^{-1})_{\alpha i} p_\alpha a^{ij}(Q) p_\beta (J^{-1})_{\beta j}.\]  

(4.60)

One can try other remedies, e.g.

\[P_i = (P_\ell^i + P_r^i)/2, \quad P_i = \sqrt{P_\ell^i P_r^i}, \quad P_i = \sqrt{P_r^i P_\ell^i},\]  

(4.61)

e etc., but they appear too artificial. It does seem unavoidable to work with two different type of momenta in Quantum mechanics, left and right, and transform each one accordingly. Formula (4.59) appears to offer slight advantages in this regard. In particular, for the free particle in polar coordinates, we find

\[H^{\ell\ell} = p_\ell^2 + p_r^2, \quad H^{r\ell} = p_r^2 + p_\ell^2,\]  

(4.62)

and each one of these formulae is satisfactory. In general,

\[h^{-2}(H^{\ell\ell} - H^{r\ell}) = h^{-2} \sum \left( (J^{-1})_{\alpha i} p_\alpha + h (J^{-1})_{\alpha i,\alpha} \right) a^{ij} (J^{-1})_{\beta j} p_\beta - h^{-2} \sum (J^{-1})_{\alpha i} p_\alpha a^{ij} (J^{-1})_{\beta j} p_\beta + h^{-1} \sum (J^{-1})_{\beta i} p_\beta a^{ij} (J^{-1})_{\mu j,\mu} - h^{-1} \sum (J^{-1})_{\beta i} p_\beta a^{ij} (J^{-1})_{\mu j,\mu} - h^{-1} \sum \left[ (J^{-1})_{\mu j,\mu} a^{ij}, (J^{-1})_{\beta i} p_\beta \right] a^{ij},\]

(4.63)

\[= \sum (J^{-1})_{\beta i} \ln \det(J) \psi (J^{-1})_{\psi j} a^{ij},\]

(by 4.64)

where we used the formula

\[= \sum_{\mu} (J^{-1})_{\mu j,\mu} = \sum (J^{-1} J_{\mu j} J^{-1})_{\mu j} = \sum (J^{-1})_{\mu \varphi} J_{\varphi \psi,\mu} (J^{-1})_{\psi j}\]

(by 4.42)

\[= \sum_{\psi} (\ln \det(J))_{\psi} (J^{-1})_{\psi j}.\]

(4.64)

Let us return now to the formula (4.37). It can be looked at from a slightly different perspective, if we notice that \(\Psi(p) = p\) whenever

\[\det(J) = \text{const} \neq 0.\]  

(4.65)
Namely, from formulae (4.33,34) we find that
\[
\Phi_\ell(p_i) - \Phi_\ell(p_i) = \sum (J^{-1})_{\alpha i} p_{\alpha} - p_{\alpha} (J^{-1})_{\alpha i} = \sum [(J^{-1})_{\alpha i}, p_{\alpha}]
\]
\[
= -h \sum (J^{-1})_{\alpha i,\alpha} \quad \text{[by (4.64)]} = h \sum (J^{-1})_{\alpha i} (\ln \det(J))_{\alpha i}.
\]
Thus, the condition of constant \(\det(J)\) (4.65) is necessary and sufficient to have the left and right formulae coincide, and thus provide a unique lift from an automorphism \(\Phi\) of \(C_q\) into a Quantum automorphism \(\Phi\) of \(C_{p,q}\). That a polynomial map \(\Phi\) with a constant non-zero \(\det(J)\) does indeed define an automorphism of \(C_q\), has been conjectured originally by Keller in [5]; this conjecture is known as the Jacobian Conjecture, and it is related to many other open problems in algebra; see, e.g., reviews in [2]. Let us discuss this Conjecture, thereafter called Conjecture \(K\), from the physical point of view. First, since an automorphism of \(\mathcal{F}[q]\) extends, via formulae (4.12), to a Poisson automorphism of \(\mathcal{F}[q,p]\), Conjecture \(K\) is implied by the more general symplectic

**Conjecture S.** A polynomial Poisson endomorphism of \(\mathcal{F}[p,q]\) is an automorphism. (In other words, if \(P_i, Q_i \in \mathcal{F}[p,q]\) are such that
\[
\{P_i, P_j\} = \{Q_i, Q_j\} = 0, \quad \{P_i, Q_j\} = \delta_{ij}, \quad 1 \leq i, j \leq N,
\]
then the \(P_i\)’s and the \(Q_i\)’s can be re-expressed as polynomials in the \(P\)’s and the \(Q\)’s. In other words still, \(\mathcal{F}[P,Q] = \mathcal{F}[p,q]\).)

Vice versa, the symplectic Conjecture \(S\) is implied by the Conjecture \(K\). Indeed, if the form \(dp \wedge dq\) is preserved then so is the volume form \((dp \wedge q)^\wedge N\); thus, the \(\det(J)\) in this case equals to 1.

The symplectic Conjecture \(S\) is a quasiclassical limit of the Quantum

**Conjecture Q.** Let \(W_N = W_N(k; h)\) be the \(h\)-scaled Weyl algebra over a commutative ring \(k\), (see, e.g., [1]) with the generators \(q_1, \ldots, q_N, p_1, \ldots, p_N\) and the relations
\[
[q_i, q_j] = [p_i, p_j] = 0, \quad [p_i, q_j] = h\delta_{ij}, \quad 1 \leq i, j \leq N.
\]
If \(Q_1, \ldots, Q_N, P_1, \ldots, P_N \in W_N\) are such that
\[
[Q_i, Q_j] = [P_i, P_j] = 0, \quad [P_i, Q_j] = h\delta_{ij}, \quad 1 \leq i, j \leq N,
\]
then the \(q_i\)’s and \(p_i\)’s can be re-expressed as polynomials in the \(P\)’s and \(Q\)’s (with coefficients in \(k[h]\) or \(k_h = k[[h]]\) depending upon the version of \(W_N\)).

In-between Conjectures \(S\) and \(Q\) is located

**Conjecture C–Q.** (i) Every Poisson endomorphism (resp. automorphism) of \(\mathcal{F}[p,q]\) can be quantized; (ii) Such quantization is unique over \(k[[h]]\).

Quantization is certainly nonunique over \(k[[h]]\). For example,
\[
P_i = \psi(h)p_i, \quad Q_i = q_i/\psi(h), \quad i = 1, \ldots, N,
\]
is a quantum automorphism for any \(\psi(h) \in 1 + hk[[h]]\), and it reduces to an identical Poisson map for \(h = 0\) no matter what \(\psi(h)\) is; such nonuniqueness, therefore, attaches to every Quantum endomorphism. On the other hand, results of Wollenberg [9, 3] show that the (i) part of the Conjecture \(C–Q\) fails for infinitesimal endomorphisms, i.e., derivations. (See also the last Remark at the end of this Section.)
Conjectures $K$ and $S$ have noncommutative analogs.

**Conjecture $K$.** Let $R$ be an associative ring and $R\langle x \rangle = R\langle x_1, \ldots, x_m \rangle$ a ring of polynomials in noncommuting variables $x_1, \ldots, x_m$ with coefficients in $R$ which do not necessarily commute with the $x_i$'s. Let $F_1, \ldots, F_m \in R\langle x \rangle$ be such that the Jacobian matrix $J(F)$:

$$J(F)_{ij} = \frac{\partial \sim F_i}{\partial x_j} \in Op_0(R\langle x \rangle)$$

(4.71)

is invertible, so that there exists a matrix $\mathcal{M} \in \text{Mat}_m(Op_0(R\langle x \rangle))$ such that

$$\mathcal{M}J(F) = 1.$$  

(4.72)

Then there exist polynomials $G_1, \ldots, G_m \in R\langle x \rangle$ such that

$$G_i(F_1, \ldots, F_m) = x_i, \quad 1 \leq i \leq m.$$  

(4.73)

**Conjecture $S$.** In $R\langle p,q \rangle = R\langle p_1, \ldots, p_N, q_1, \ldots, q_N \rangle$, let the noncommutative Hamiltonian structure [7] be given by the Hamiltonian matrix

$$B = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$  

(4.74)

If $P_1, \ldots, P_N, Q_1, \ldots, Q_N \in R\langle p,q \rangle$ preserve the Hamiltonian structure $B$:

$$JBJ^\dagger = B,$$  

(4.75)

then $p_1, \ldots, p_n, q_1, \ldots, q_N \in R\langle P,Q \rangle$. (The adjoint $J^\dagger$ of $J$ in formula (4.75) is taken in the noncommutative sense defined in [7].)

We conclude this Section by mentioning two other versions of Conjecture $K$:

**Conjecture $K^{\text{var}}$.** If $R$ is commutative and $F_1, \ldots, F_m \in R\langle x \rangle$ are such that the matrix $J^{\text{var}}(F) \in \text{Mat}_m(R\langle x \rangle)$ [7] is invertible, where

$$J^{\text{var}}(F)_{ij} = \frac{\delta F_i}{\delta x_j} \in R\langle x \rangle,$$  

(4.76)

$$\frac{\delta F_i}{\delta x_j}(\chi) \equiv \frac{\partial \sim F_i}{\partial x_j}(\chi) (\text{mod } [R\langle x \rangle, R\langle x \rangle]), \quad \forall \chi \in R\langle x \rangle,$$  

(4.77)

then the map $F : R^m \to R^m$ is a polynomial automorphism.

**Conjecture $C-K$.** (A noncommutative analog of the Quantization Conjecture $C-Q$). Let $f : k^m \to k^m$ be a polynomial map with an invertible Jacobian (resp. automorphism). Then one can find a set of polynomials $F_1, \ldots, F_m \in k\langle x \rangle$ with an invertible Jacobian (in either of the two meanings, (4.71) or (4.76)) (resp. automorphism) such that $f_i(x) = F_i(x)$, $i = 1, \ldots, m$, when all the $x_i$'s are allowed to commute between themselves.

The Conjecture $C-K$ is obviously true for tame automorphisms (generated by $GL_m(k)$ and triangular maps), and thus is true for $m = 2$ ([4, 6]). The same conclusion applies to the (i) part of Conjecture $C-Q$ for the case $N = 1$. 

References


The * attached to a citation marks the publisher that demands, as a condition of printing a paper in the publisher’s journal, that all authors of creative works surrender and hand in to the publisher the copyright to the fruits of their labors. The publishers so noted do not include those in Cuba, North Korea, and other savage places, where such a policy is not a matter of free choice but is state-mandated.